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## Constraints on the Space Density of Methane Dwarfs and the Substellar Mass Function from a Deep Near-Infrared Survey

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### ABSTRACT

We report preliminary results of a deep near-infrared search for methane-absorbing brown dwarfs; almost five years after the discovery of Gl 229b, there are only a few confirmed examples of this type of object. New J band, wide-field images, combined with pre-existing R band observations, allow efficient identification of candidates by their extreme (R-J) colours. Follow-up measurements with custom filters can then confirm objects with methane absorption. To date, we have surveyed a total of 11.4 square degrees to  $J \sim 20.5$  and  $R \sim 25$ . Follow-up CH<sub>4</sub> filter observations of promising candidates in 1/4 of these fields have turned up *no* methane absorbing brown dwarfs. With 90% confidence, this implies that the space density of objects similar to Gl 229b is less than 0.012 per cubic parsec. These calculations account for the vertical structure of the Galaxy, which can be important for sensitive measurements. Combining published theoretical atmospheric models with our observations sets an upper limit of  $\alpha \leq 0.8$  for the exponent of the initial mass function power law in this domain.

*Subject headings:* Galaxy: stellar content – infrared: stars – stars: low-mass, brown dwarfs – surveys

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## 1. Introduction

Brown dwarfs are star-like objects that span the mass range between the gas giant planets like Jupiter and the least massive stars. Although luminous early in their evolution due to gravitational contraction and deuterium burning, brown dwarfs have insufficient mass to ignite and sustain hydrogen fusion in their cores. The discovery and confirmation of a small number of brown dwarfs in the last few years has renewed interest in these objects after more than a decade of difficult and unsuccessful searches.

One object in particular, Gl 229b, has been the focus of widespread study, since it is at least 10 times less luminous than the lowest-mass stars, and its near infrared spectrum shows broad, deep, methane absorption features such as those seen in Jupiter (Nakajima *et al.* 1995, Oppenheimer *et al.* 1995, Geballe *et al.* 1996). Recently, several groups have undertaken large surveys for older, field brown dwarfs (*i.e.* using 2MASS, Kirkpatrick *et al.* 1999, and DENIS, Delfosse *et al.* 1997). These programs have identified significant numbers of more luminous substellar objects, but there are only a handful of additional examples of methane absorbing, very low luminosity brown dwarfs like Gl 229b, all reported very recently (Strauss *et al.* 1999, Burgasser *et al.* 1999).

In this paper, we report the preliminary results of a deep, wide-field survey for such “methane brown dwarfs.” This survey employs a two-step approach to this task: efficient identification of candidates through their red (R-J) colours, followed by confirmation through methane filter imaging.

## 2. Survey Strategy

The deep H and K band methane absorption features are a distinctive and defining feature of these objects. Suitably designed custom filters can provide enormous contrast between the methane absorption and the adjacent continuum, a contrast inconsistent with any known continuum emission process or non-methane absorption feature. Rosenthal et al. (1996) showed a detection of Gl 229b using a (relatively inefficient) 1% bandwidth variable filter tuned to these wavelengths.

The bright sky background in the H and K photometric bands hampers efficient, wide-field surveys. Instead, we take advantage of another identifying property of brown dwarfs to pre-select candidates. The spectral energy distribution of old brown dwarfs peaks in the J band, (Nakajima *et al.* 1995), and, coupled with molecular absorptions at shorter wavelengths, this profile produces extreme ( $R - J$ ) colours. For example, Gl 229b has  $(R - J) \gtrsim 9$  (Matthews *et al.* 1996, Golimowski *et al.* 1998), much redder than even the

coolest stars (an M6 dwarf has  $(R - J) \sim 4$  - Bessel, 1991).

Efficient J band measurements are possible using wide-field, prime focus cameras, and we further streamline the survey by using *pre-existing* R band observations from a high-redshift supernova search (see section 3.1). Subsequent measurements of promising targets with the custom filters then isolate the methane absorbing brown dwarfs. Such follow-up is essential in eliminating false detections due to supernovae, asteroids, and high proper-motion objects, (some of which are interesting in themselves). Extremely red galaxies can also appear; such galaxies will be the subject of a separate follow-up investigation.

The pre-existing R data have a typical ( $3\sigma$ ) limiting magnitude of  $R \sim 25$ . We chose a limiting magnitude of  $J \sim 20.5$  for the near infrared survey, in order to identify effectively all candidates with  $(R-J) \gtrsim 5$ . Note that G1 229b would have  $J \sim 20$  at a distance of 100 pc, so this R-J survey is well-matched to the vertical scale height of the Galactic disk.

### 3. Observations and Results

#### 3.1. R and J Band Surveys

The R band observations took place over the period 1995–1997 as part of the High-Z Supernova Search Team cosmology project (Schmidt *et al.* 1998). This supernova survey comprises over 300 high galactic latitude fields, each 15 arcminutes square, located within a few degrees of the celestial equator. We registered and averaged typically six individual flat-fielded exposures to create the final R frame. Photometric calibration came from galaxy number counts and the magnitude relations in Metcalfe *et al.* (1991), a technique sufficiently accurate ( $\pm 0.2$  mag) to identify candidates with extreme (R-J) colours.

We observed 40 of these fields (2.6 square degrees in total) in the J band between 11 and 13 October 1997, using the Omega Prime near infrared camera (Bizenberger *et al.* 1998) mounted at the prime focus of the 3.5 m telescope on Calar Alto. J band observations of a further 140 fields (9.0 square degrees) took place in April 1998, October 1998, and May 1999. None of the recently-reported methane dwarfs lie in our fields. Weather conditions were excellent for all measurements. We applied standard sky subtraction and flat-fielding routines to remove the effects of sky background and pixel to pixel gain variations. Several of the UKIRT faint standards (Casali and Hawarden, 1992) served as photometric reference. The final J band mosaic images are  $15' \times 15'$ , well-matched to the R fields.

We used the SExtractor package (Bertin and Arnouts 1996) to identify objects in the J band mosaic and derive brightness and morphology information. Using the J band locations

for the R band photometry produced a catalog of all objects detected in the near-infrared. This approach focuses on potentially interesting targets (*i.e.* large  $R - J$ ) while avoiding the 80% of R detections which are not seen at J. Nevertheless, the 40 data sets from October 1997 yielded information on approximately 35,000 objects.

### 3.2. Follow-Up Observations of Candidates

A small number of sources, typically 1 per field, display very red colours and merit further observations with the methane filters. Figure 2 shows R and J band sub-images of a candidate with  $(R-J) > 7.1$ . Between 11 and 16 October 1998, we observed a total of 44 such objects from the first set of 40 fields, using the K band methane filters in Omega Prime. Again, standard sky-subtraction and flat-fielding techniques removed the background and pixel to pixel gain variations. The  $(R-J)$  cut-off for follow-up varied by approximately 0.1 mag from field to field, but in all cases was less than  $(R-J) = 5.6$ .

For convenience, we will hereafter refer to the methane filters as  $K_C$  (K continuum: 1.95-2.2  $\mu\text{m}$ ), and  $K_A$  (K absorption: 2.15-2.4  $\mu\text{m}$ ).  $K_C$  and  $K_A$  are not standard photometric filters, but they correspond closely to the lower and upper halves of the K band, respectively. Figure 2 plots  $(K_C - K_A)$  for the 44 candidates against the “stellarity index” determined by SExtractor. A negative  $(K_C - K_A)$  points to the presence of methane, and a higher stellarity means more star-like. Also plotted is the methane colour and stellarity of Gl 229b derived from the images shown in Figure 1. None of the 44 candidates, and in particular, none of the more star-like objects, remotely approach Gl 229b in terms of  $K_C - K_A$  colour. In fact, almost all are somewhat red, not “blue,” even over this very short range of wavelengths.

## 4. The Space Density of Methane Brown Dwarfs like Gl 229b

What is the upper limit to the space density of objects like Gl 229b that is consistent with our seeing none? The answer depends on both counting statistics and the effective survey volume. Observing zero events in a single counting experiment can occur if the average number of events is nonzero. To set a 90% confidence level on the minimum number of expected events, we must calculate the expectation value of a Poisson distribution whose probability of zero events is 10%. This value is approximately 2.3. Hence, with 90% confidence, our observations set an upper limit of 2.3 to the mean number of methane brown dwarfs in our survey volume.

The effective survey volume  $V_{\text{eff}}$  depends in turn on the intrinsic luminosity of the

sources, the angular size and galactic coordinates of the fields, and the vertical structure of the galaxy. The volume enclosed by a field of solid angle  $\Omega_f$  to a distance  $r_{max}$  is  $\frac{1}{3} \Omega_f r_{max}^3$ . The forty fields then enclose a total search volume of 350 pc<sup>3</sup>. Depending on the vertical distribution of the targets in the Galaxy, however, the combination of high galactic latitudes and relatively large  $r_{max}$  will reduce the *effective* survey volume, ( $V_{eff}$  refers to the equivalent volume in the midplane). For a single field  $i$  at galactic latitude  $b$ , the effective volume is:

$$V_{eff}^i = \Omega_f \int_0^{r_{max}} r^2 e^{\frac{-|Z_0+r \sin b|}{h_z}} dr, \quad (1)$$

where  $h_z$  is the scale height for the target objects and  $Z_0 = 12$  pc is the vertical displacement of the Sun with respect to the Galactic midplane (Gilmore, 1989). Due to kinematic heating of the Galactic disk,  $h_z$  is a function of the age of the population. Gl 229b has a best-fit age between 2-4 Gyr based on atmospheric models and its measured luminosity (Allard *et al.* 1996, Burrows *et al.* 1997, Matthews *et al.* 1996). This corresponds roughly to the mean age of F5V stars, which have  $h_z=190$  pc, (Allen, 1976). Combining these effects, we calculate an effective survey volume  $V_{eff} = \Sigma V_{eff}^i \sim 190$  pc<sup>3</sup>, and we can say with 90% confidence that the space density for objects like Gl 229b is less than  $n_0 = 2.3 / 190 = 0.012$  pc<sup>-3</sup>. For a scale height appropriate to the minimum possible age for Gl 229b (0.5 Gyr, Allard *et al.* 1996), our  $V_{eff}$  drops to 165 pc<sup>3</sup> and  $n_0 < 0.014$ . For faint objects like Gl 229b, our type of deep, relatively small area search is very effective. In fact, in a single night of observations, we cover a faint-object survey volume comparable to the entire DENIS project.

## 5. Limits on the Mass Function of Methane Brown Dwarfs

The upper limit to the space density established in the previous section refers to brown dwarfs “similar to Gl 229b,” that is, extremely red objects with  $M_J \approx 15.4$  and deep methane absorption in the K band. Younger or more massive objects will be brighter and therefore visible to a greater distance. On the other hand, brown dwarfs spend a relatively small fraction of their lifetimes in this early, hot phase, and higher effective temperatures may not allow the formation of CH<sub>4</sub>. In this section, we combine published theoretical atmospheric models with our observations to estimate the number of methane absorbing substellar objects that we would expect in our survey. The probability of seeing such an object depends on its mass, age, and the volume within which we could detect it:

$$d\langle N \rangle = P_m(m) P_t(t) P_V(m, t) dm dt dV \quad (2).$$

$P_m$  is the substellar initial mass function (IMF), with suitable normalization to give the number of objects per cubic parsec. We adopt the standard power law form of the IMF:  $dn(m) = C \cdot m^{-\alpha} dm$ . Here,  $dn(m)$  denotes the number of objects per cubic parsec with mass between  $m$  and  $m + dm$  and  $C$  is a constant. Surveys of M dwarfs within 8 pc of the sun give a local space density of  $\sim 0.065 \text{ pc}^{-3}$  and a power law exponent  $\sim 0.8$  (*e.g.*, Leinert *et al.* 1997, Henry and McCarthy 1992). Setting the integral of the mass function for M dwarfs to this space density gives the IMF normalization at the M Dwarf - Brown dwarf boundary. We do not assume that the exponent has the same value for brown dwarfs. Continuity of the mass function at the boundary then requires that  $C$  be a function of  $\alpha$ .

The second term in equation 2,  $P_t(t)$ , is the age distribution of substellar objects. For simplicity, we assume a constant mean galactic star formation rate,  $P_t = t_{max}^{-1}$ , where  $t_{max}$  is  $\sim 9$  Gyr, the maximum age of the Galactic disk population (Winget *et al.*, 1987). We adopt a lower bound to the age of field brown dwarfs,  $t_{min} = 0.5$  Gyr, typical of the minimum age of stars in the solar neighbourhood and the maximum age of stars in identifiable clusters (also see Section 6).

Although young substellar objects are bright, successful classification in our survey requires the presence of detectable methane. Strong  $CH_4$  absorption will not occur above a certain critical effective temperature,  $T_c \approx 1200$  K (Tsuiji *et al.* 1995, Burrows and Sharp 1999). Because the effective temperature  $T_{eff}$  is a function of the age (and mass) of the object,  $P_t(t)$  includes a factor  $f_{CH_4}$  describing the detectability of methane. We use an analytic interpolation of the  $T_{eff}$  curves of Burrows *et al.* (1997) to calculate the effective temperature for each mass and age, and then set  $f_{CH_4}$  to zero or one depending on whether  $T_{eff} > T_c$  or vice versa.

$P_V(m, t)$  is just  $V_{eff}$  from equation 1, with the upper integration limit corresponding to the current values of  $m$  and  $t$ . Burrows *et al.* (1997) calculate the  $M_J$  for substellar objects as a function of mass and age, and again we employ an analytic interpolation of their curves. The scale height  $h_z$  depends on the age  $t$  of the object and is calculated based on a smooth fit to the data in section 119 of Allen (1976).

Combining these elements leads to a numerically solvable equation for the expected number of substellar objects:

$$\langle N(\alpha) \rangle = \int_{0.02}^{0.075M_\odot} dm C m^{-\alpha} \int_{t_{min}}^{t_{max}} dt \frac{f_{CH_4}}{t_{max}} \sum_{fields i} d\Omega \int_0^{r_{max}} dr r^2 e^{\frac{-|Z_0+r \sin b|}{h_z}}, \quad (3)$$

Solving Equation 3 with  $\langle N \rangle = 2.3$ , the upper limit to the number of detections in our

survey, gives a limit on  $\alpha$ , the power law index of the mass function. With 90% confidence, our observations demonstrate that  $\alpha \leq 0.8$  in the substellar regime. Note that this conclusion allows continuity of the power law index across the hydrogen burning limit.

## 6. Discussion

Kirkpatrick *et al.* (1999) report the discovery of 7 new non-methane field brown dwarfs in the first  $\sim 1\%$  of the 2MASS survey. They did not find any clear examples of methane-absorbing brown dwarfs. Using the sensitivity, field coverage and other particulars of 2MASS in Equation 3 yields  $\langle N \rangle = 0.7$  for the expected number of methane absorbing brown dwarfs, consistent with their finding none. Setting  $f_{CH_4} \equiv 1$  in equation 3 gives  $\langle N \rangle = 4.2$  for the *total* number of brown dwarfs expected, not just those with methane absorption. The 90% confidence interval of a distribution with mean 4.2 marginally includes an experiment with 7 detections. DENIS has qualitatively lower K band sensitivity, and it is no surprise that no methane dwarfs appeared in the Delfosse *et al.* preliminary survey.

We can also compare our calculations to the recent report (Burgasser *et al.* 1999) of 4 methane-absorbing brown dwarfs in a subsequent 2MASS survey area considerably larger than that presented in Kirkpatrick *et al.* (1999). Scaling the expectations for methane brown dwarfs in the Kirkpatrick *et al.* sample up to the larger area gives  $\langle N \rangle \approx 3.5$ , completely consistent with the number of objects discovered.

These calculations highlight one of the strengths of using the methane absorbing brown dwarfs to constrain the substellar mass function. The survey volume for non- $CH_4$  absorbers is overwhelmingly dominated by the youngest, hottest, objects, and is therefore very dependent on the selection of the lower age boundary  $t_{min}$  in Equation 3. However, the absence of methane in the atmospheres of such hot objects makes the determination of  $\langle N \rangle$  for  $CH_4$ -absorbers insensitive to assumptions about  $t_{min}$ . For example, setting the lower integration limit to 0.1 Gyr more than doubles the expected *total* number of substellar objects, but increases  $\langle N \rangle$  for the methane dwarfs by less than 10%. (Note also that reducing  $t_{min}$  to 0.3 Gyr brings the prediction of Equation 3 into complete agreement with the  $N = 7$  total brown dwarfs found by 2MASS.)

Two important caveats deserve mention. First, our identification technique depends on the presence of detectable methane. Aside from the temperature effects discussed above, there are theoretical calculations which suggest that cloud formation in the stellar atmosphere may suppress the contrast in the methane band features for certain combinations of effective temperature and surface gravity (see, for example, Marley *et al.* 1999). Based on our

measurements of Gl 229b and the spectra of Strauss *et al.* 1999 and Burgasser *et al.* 1999, we would have easily identified all of the half-dozen known objects in this class. Nevertheless, any survey, including ours, which depends on a partial darkening of the K band may be biased, should cloud formation prove to be an important process for these objects.

The second caveat concerns stellar multiplicity. Gl 229b is in a binary system only 6 pc from the sun. We were easily able to detect and identify the unusual character of Gl 229b using our filter set (Figure 1), but it would have been impossible to separate the stars at any distance approaching the  $r_{max} \sim 100$  pc cited above. The problem of dynamic range and angular resolution is also a central issue for the all-sky surveys, since they typically have spatial sampling 3-5 times coarser than ours. (None of the recently reported methane dwarfs are in obvious multiple systems.) And for everyone, it is an uncomfortable fact of life that the majority of the search volume lies at the greatest distances for which the spatial resolution is poorest.

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Fig. 1.— (top) Profiles of our custom filters superimposed on a spectrum of Gl 229b. Tailoring the filter profiles to the expected methane feature produces an efficiency gain of a factor 12 over 1% narrow band filters (*e.g.*, Rosenthal *et al.* 1996). (bottom) Images of Gl 229b in the continuum  $K_C$  (left) and absorption  $K_A$  (right) filters. The primary star image is saturated in the gray regions

Fig. 2.— (top) J band (left) and R band (right) images of a candidate with  $(R-J) > 7.1$ . (bottom)  $K_C - K_A$  Colour vs Stellarity for the 44 objects with extreme  $(R-J)$  colour. Also plotted are the measurements for Gl 229b. None of the candidates resembles a methane-absorbing brown dwarf.



